

## **Summary of ongoing TARDEC work in metamaterials relevant to NATO SET-181**

The Primary Investigators in this research Program are Dr. Elena Bankowski and Dr. Thomas Meitzler at the TARDEC Electrified Armor Laboratory and Professor Andrei Slavin, Chair, Physics Department of the Oakland University.

The ongoing technical activities in nanoelectronics (spin-torque microwave detectors – STMD) and metamaterials relevant to SET- 181 are briefly described below.

The first research section describes our efforts in “Microwave energy harvesting using spintronic devices”, while the second section is devoted to the “Spintronic metamaterials”. The third section is devoted to our understanding of future capabilities and novel functionalities of Army-related metamaterials.

### **UNIQUE FACILITIES AND EQUIPMENT USED:**

Research on both above mentioned topics is being performed at the TARDEC Electrified Armor Laboratory using a microwave anechoic chamber and relevant microwave measurement instruments. Numerical simulations are performed using the “Beowulf” supercomputer cluster at the Physics Department of the Oakland University.

#### **1. Microwave energy harvesting using arrays of passive nano-scale spintronic devices**

Our primary goal in this effort is to investigate different regimes of operation of nano-sized spin-torque microwave detectors (STMD) when they are used for the purpose of microwave energy harvesting. We are studying two regimes: a traditional small-angle in-plane (IP) regime and a new large-angle out-of-plane (OOP) regime of microwave magnetization precession in the STMD. Our goal is to develop a theoretical approach for the optimization of the microwave characteristics of such a device operating in IP and OOP regimes.

Our secondary goal is to develop analytic methods to optimize the noise-handling characteristics of STMDs based on magnetic tunnel junctions (MTJ) and operating as sensitive detectors of microwave radiation in the regime of IP precession. These devices are intended for future applications in sensor enhanced armor and it is necessary to develop analytic methods to optimize the performance of these MTJ devices in a very noisy environment.

The operation of a nano-scale STMD in the IP-regime is based on the diode effect in MTJ described in [1], which was further developed in [2, 8]. The operating characteristics of STMD, when optimized, will surpass the characteristics of semiconductor detectors of microwave radiation both in sensitivity and in noise-handling capabilities. The idea to use STMD for microwave detection and energy harvesting is new, but it is based on the results of recent theoretical [2, 3, 4]

Report Documentation Page				Form Approved OMB No. 0704-0188	
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1. REPORT DATE <b>21 AUG 2013</b>		2. REPORT TYPE <b>Report</b>		3. DATES COVERED <b>03-03-2013 to 18-07-2013</b>	
4. TITLE AND SUBTITLE <b>Summary of ongoing TARDEC work in metamaterials relevant to NATO SET-181</b>				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) <b>Elena Bankowski ; Thomas Meitzler ; Andrei Slavin</b>				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) <b>U.S. Army TARDEC, 6501 East Eleven Mile Rd, Warren, MI, 48397-5000</b>				8. PERFORMING ORGANIZATION REPORT NUMBER <b>; #24157</b>	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) <b>U.S. Army TARDEC, 6501 East Eleven Mile Rd, Warren, MI, 48397-5000</b>				10. SPONSOR/MONITOR'S ACRONYM(S) <b>TARDEC</b>	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S) <b>#24157</b>	
12. DISTRIBUTION/AVAILABILITY STATEMENT <b>Approved for public release; distribution unlimited</b>					
13. SUPPLEMENTARY NOTES <b>Nato SET-181 Report</b>					
14. ABSTRACT <b>The Primary Investigators in this research Program are Dr. Elena Bankowski and Dr. Thomas Meitzler at the TARDEC Electrified Armor Laboratory and Professor Andrei Slavin, Chair, Physics Department of the Oakland University. The ongoing technical activities in nanoelectronics (spin-torque microwave detectors ? STMD) and metamaterials relevant to SET- 181 are briefly described below. The first research section describes our efforts in ?Microwave energy harvesting using spintronic devices?, while the second section is devoted to the ?Spintronic metamaterials?. The third section is devoted to our understanding of future capabilities and novel functionalities of Army-related metamaterials.</b>					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT <b>Public Release</b>	18. NUMBER OF PAGES <b>8</b>	19a. NAME OF RESPONSIBLE PERSON
a. REPORT <b>unclassified</b>	b. ABSTRACT <b>unclassified</b>	c. THIS PAGE <b>unclassified</b>			

and experimental [5, 6, 8] investigations, and on the prior achievements of the authors in the defense sensor technology [5, 6]. This exploratory research in the field of spintronics will lead to the development of novel nano-scale sensors of microwave radiation suitable for integration into protective layers of ground vehicles.

The other innovation, being investigated is a discovery of a new regime of operation of a spin-torque microwave detector (STMD), characterized by the threshold excitation of large-amplitude out-of-plane (OOP) microwave precession by a relatively weak microwave input signal (OOP-regime). A patent application [7] has been submitted to the U.S. Patent and Trademark Office in October, 2011 on this idea. In such a regime, the STMD works as a non-resonance threshold detector of low frequency microwave signals and is characterized by a large output DC voltage and extraordinary high differential sensitivity near the threshold. These unique properties will lead to the development of nano-scale microwave detectors operating as cores of microwave energy harvesting devices. These devices are passive, they do not require power sources and are capable of microwave energy harvesting on the battlefield or in urban environments.

The survivability of ground vehicles on the battlefield depends on rapid and reliable detection of enemy threats. This situational awareness task can be achieved by detection of microwave radiation emitted by enemy radar and aiming systems. Battlefield microwave detectors should possess a number of qualities, namely: 1) they should perform under the influence of ionizing radiation, 2) should be of a small size and weight, and 3) have little or no power consumption. Current semiconductor diode detectors do not meet these requirements. Spintronic detectors and energy harvesters are not vulnerable to ionizing radiation, can be scaled down to nanometer sizes, do not require built in power sources, can operate with a minimal external energy from microwave sources on the battlefield, and they can be embedded into some types of armor.

The STMD in the OOP-regime was used as a base element for microwave energy harvesting. The energy conversion rate  $\zeta$  of an STMD in the OOP regime may be estimated as

$$\zeta = \frac{P_{DC}}{P_{RF}} \approx \frac{1}{2} \left( \frac{I_{th}(\omega)}{I_{RF}} \right)^2 \left( \frac{\omega}{\omega_0} \right)^2 \quad (1.1)$$

where  $P_{DC}$  is the output DC power under the influence of input microwave power  $P_{RF}$ ,  $\omega_0 \equiv \omega_0(a_s) = (1 - a_s^2)^{-1/2}$ ,  $a_s \approx P^2$ . The maximum possible conversion rate  $\zeta_{max} \approx \frac{0.5\omega^2}{\omega_0^2} \approx 3.5\%$  is reached in the case when  $I_{RF} = I_{th}(\omega)$ . We believe that this energy conversion rate is sufficiently large for practical applications in microwave energy harvesting [7, 8]. Thousands of passive spintronic nano devices could be coupled into an array forming, as a result, a passive energy-harvesting metamaterial.

## RESULTS:

- A theoretical description of the operation of the MTJ microwave detectors in the IP-regime at zero temperature and in the presence of thermal fluctuations associated with a finite temperature.
- Calculation of the equivalent microwave power of noise, signal-to-noise ratio of the detector and the minimum detectable microwave power of the STMD.
- Optimization of radar detectors noise-handling characteristics.
- Discovery of the novel regime of operation of a STMD based on the threshold excitation of large-angle out-of-plane (OOP) microwave precession under the influence of a relatively weak microwave signal [7].
- Calculation of the output voltage of such an STMD as a function of the frequency and magnitude of an external signal. The typical voltage dependence on the input microwave current is shown in Fig.1.1, where the solid line shows the results of the analytic theory while the symbols show the results of numerical calculations.

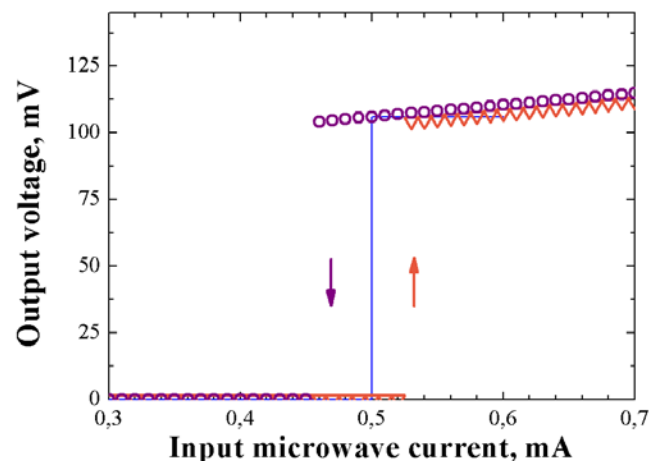


Fig.1.1 Output DC voltage of the STMD energy harvester as a function of the external microwave current.

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## ***2. Theory of non-reciprocal on-wafer microwave devices based on nano-structured magnetic metamaterials***

One important objective of this ongoing research effort is to study static and dynamic properties of spintronic metamaterials formed by planar arrays of magnetic dots coupled by magneto-dipole interaction. In particular, we are interested in the non-reciprocal properties of collective magnetic excitations (spin waves) propagating in such metamaterials for the purpose of development of miniature microwave isolators and circulators. One of our goals is the development of an engineering theory of on-chip microwave nonreciprocal devices (isolators and circulators) that employ natural (either shape or/and crystallographic) anisotropy of magnetic elements and will not require external bias magnetic fields for their operation. The artificial nano-structured magnetic metamaterials based on coupled arrays of anisotropic magnetic elements can provide a solution to this important technological problem. These planar nonreciprocal magnetic metamaterials could be easily integrated into standard planar semiconductor fabrication techniques. They will improve performance of microwave signal processing devices, substantially reduce size and weight of such devices by eliminating permanent magnets and will reduce fabrication costs for the Army by using standard planar fabrication processes. The size reduction related to the new on-chip technology of fabrication of non-reciprocal devices will also lead to the overall reduction in power consumption of microwave signal processing devices for defense applications.

We were also interested in the electromagnetic wave scattering from nano-structured non-reciprocal magnetic metamaterials to determine their usability as non-reflective, cloak-type coatings for ground vehicles.

In the course of our research we are developing an engineering theory of miniature on-chip non-reciprocal devices capable of working without external permanent magnets and based on magnetic metamaterials comprised of coupled arrays on nano-scale magnetic particles (cylindrical pillars) having the axis of shape anisotropy that is perpendicular to the cylinder base. We are also studying theoretically the reflection of electromagnetic waves from nano-structured magnetic metamaterials in the effort to determine the applicability of these materials for non-reflective cloak-type coatings. This research project contributes to the Future Army forces capabilities referenced in <http://www.tradoc.army.mil/tpubs/pamndx.htm> TRADOC PAM 525-3-5, Appendix B-3. Protection required capabilities: Future Army forces require the capability to prevent the enemy from detecting, tracking, and targeting forces while operating in all environments, to reduce their capability to inflict losses.

We are studying the static properties of a proposed spintronic metamaterial (dipolarly coupled two-dimensional arrays of magnetic nano-dots having perpendicular shape anisotropy) and successfully determined the magnetic ground states of this metamaterial both analytically and numerically. We have shown that chessboard antiferromagnetic (CAFM) state is a true ground state of such a material, and also studied a long-lifetime metastable ferromagnetic (FM) state. In both states the spectra of dynamic microwave excitations – collective spin waves – were calculated analytically and numerically. We found that the ground state of such a metamaterial (and, therefore, the spectra of microwave excitations in it) could be switched by the application of a short pulse of external bias magnetic field.

The switching from an arbitrary state to the FM state can be achieved by applying a rectangular field pulse of magnetic field directed along the magnetic dot axis, while the switching to the CAFM state requires the field pulse oriented in the dot plane and having a sufficiently long trailing edge (tail). Our results proved that arrays of magnetic nano-dots can be used as a “reconfigurable” metamaterial, having rapidly switchable magnetic and microwave properties.

## RESULTS:

The obtained results proved the possibility of controllable fast switching of microwave absorption frequencies of magnetic metamaterials. We implemented a model of a two-dimensional array of identical magnetic nano-dots coupled by magneto-dipolar interaction. The dots were assumed to be cylindrical particles made from a soft magnetic material. The dots had the radius  $R$  and height  $h$  and were arranged in a square lattice, with a lattice constant  $a$ . As it was mentioned above, the two basic static states of such a metamaterial are: the FM state, shown in Fig. 2.1 (a) and the CAFM state, shown in Fig. 2.1(b). These static states can be stable simultaneously in a wide range of array's parameters (Fig. 2.1(d)). The difference of ferromagnetic resonance (FMR) frequencies  $f_{21}$  in these two states significantly exceeds the FMR line width and can reach several GHz (see Figs. 1(c) and 1(d)). An array of dipolarly coupled magnetic dots can be switched to the

FM state by applying a magnetic field pulse of sufficient amplitude directed along the dot axis. We have also shown numerically that the array in the FM state shown in Fig.2.1 can be switched to an almost ideal CAFM state shown in Fig.2.1 (b), using a spatially homogeneous magnetic field pulse directed in the plane of a dot base.

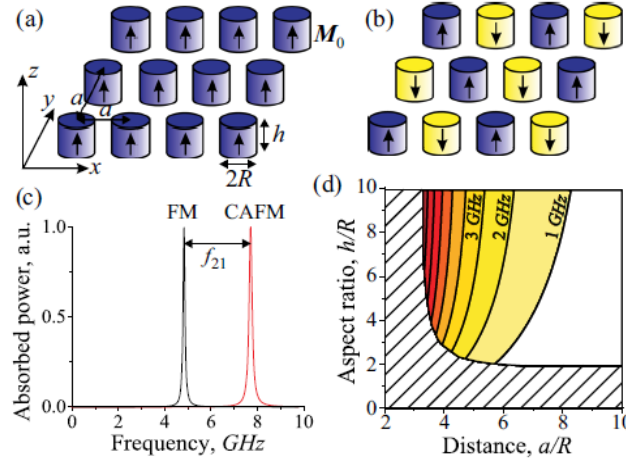


Figure 2.1: (a), (b): Sketch of magnetic dots array in the FM and CAFM ground states. (c) FMR power absorption spectra of the array in the FM and CAFM states. (d) Difference of the FMR frequencies  $f_{21}$  in two different ground states as a function of geometric parameters  $a/R$  and  $h/R$ . The region where one or both ground states are unstable is dashed.

We demonstrated that the magnetic ground state and the microwave absorption frequency of an array of magnetic nano-dots can be switched by short magnetic field pulses with duration of *tens of nanoseconds*. We could easily switch the array into the ideal FM state. Switching into the CAFM state was more difficult, and the array after the in-plane field application always contained several clusters with similar, but different CAFM configurations. This effect leads to a certain inhomogeneous broadening of the FMR peak in the resultant non-ideal CAFM state formed after switching.

We performed computer simulations of switching from FM to CAFM state in magnetic dot arrays and these simulations demonstrated formation of several different CAFM clusters as the result of the switching process. A typical result of simulation (resultant magnetic configuration of the array after switching) is shown in Fig. 2.2 (a) for the applied spatially uniform magnetic field pulse of the duration  $\tau = 40$  ns. We also calculated numerically the FMR absorption line of the resultant array in a zero external magnetic field (see Fig 2.2 b), which is showing several absorption peaks and overall inhomogeneous broadening of the FMR line caused by the array's clustering.

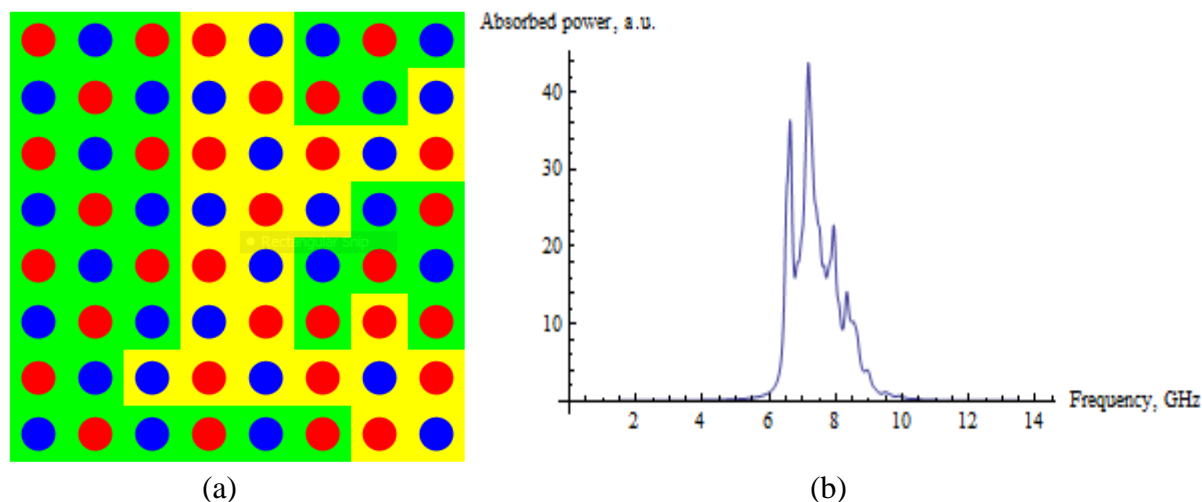


Figure 2.2: Results of numerical simulations illustrating the formation of several CAFM clusters in a magnetic dot array (spintronic metamaterial) after switching: (a) Different CAFM clusters formed after switching are shown by green and yellow shading, respectively; (b) FMR absorption spectrum of an array of magnetic nanodots shown in Fig. 3 (a) in a zero external field demonstrating several absorption peaks and substantial inhomogeneous line broadening caused by the cluster formation.

We are planning to continue this important research program and believe that further numerical modeling and simulations of absorption and reflection of electromagnetic waves by magnetic metamaterials will help us to determine their applicability for the development of novel non-reflective cloak-type coatings for ground vehicles.

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### **3. *Future capabilities and novel functionalities of possible Army-relate metamaterials.***

In the beginning of the 21 century it became clear that the progress achieved in micro- and nano-fabrication techniques will allow the fabrication of 'designed-to-order' artificial metamaterials with novel functionalities.

Possible functionalities of metamaterials that may be the most important to the Army applications include:

Solar energy harvesting - photo-electric metamaterials;

Microwave energy harvesting - spintronic metamaterials;

Non-reciprocity without magnetic field – magnonic metamaterials;

Stealth and cloaking – optical metamaterials.